Beem-Beam Induced Emittance Growth

Simulation of RHIC 2006 pp Run

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Outline

1. LIFETRAC technique and the history
2. Emittance growth simulation in RHIC
3. Comparison to the measurement data
4. A look into shorter bunch options
5. Conclusion and future work

History of the tracking technique and code for Equilibrium Distribution

1. Initial concept was proposed by J. Irwin 1989
   (J. Irwin, 3rd ICFA Workshop, Novosibirsk, 1989);

2. Concept was further developed and implemented into beam-beam simulation code "LIFETRAC" by D. Shatilov at INP
   (D. Shatilov, INP 92-79, Novosibirsk, 1992, in Russian);

3. Same concept, but slightly different method, was developed independently and implemented into beam-beam code "LFM" by T. Chen, et al. at SLAC
   (T. Chen, et al., Phys. Rev. E49, p2323, 1994);

4. Both codes were tested against multiparticle brute force tracking code "TRS". They reached good agreement
   (M. Furman, CBP Tech Note 59, 1995)

5. INP 92-79 tech-note (in Russian) was translated and published in English by D. Shatilov.
   (D. Shatilov, Particle Accelerators, Vol.52, p65, 1996)

LIFETRAC Tracking Technique
(Developed for Equilibrium Distribution)

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1. Developed to determine beam halo and life time and reduce the required CPU time by 1-2 magnitudes.

2. Beginning from the core region the beam distribution is built step by step in the amplitude space.

3. During each step only those particles fall outside of the given region in amplitude space are tracked.

4. At the end of each step the boundary of the region is moved to larger amplitude where the line of equal distribution density is.

5. The border conditions taken from the previous step connect the distributions of in/out of the region.

How does LIFETRAC Handle the Underlying Physics

The code is designed to simulate the beam tail/halo without introducing bias towards any one mechanism:

Resonance overlap

The beam-beam interaction is treated as a kick. So, it includes all overlapped and isolated resonances.

Diffusion

The global expansion of the boundary separating core and halo naturally accommodates diffusion.

Resonance streaming

Instead of using simple circular arcs as boundaries LIFETRAC used irregular shaped boundary defined by equal distribution density which naturally stretch out in the direction of Resonance streaming in the A_x-A_y plan.

Underlying Physics

Resonance overlap

When high-order resonances are wide enough, or close enough, they may overlap which leads to chaotic motion of particles moving from one resonance to another and reach larger amplitude.

Diffusion

Particles starting at locations throughout the core slowly diffuse to larger amplitudes where they move as oscillators driven by noise from the beam-beam kick. It may generate non-Gaussian tail.

Resonance streaming

Quantum fluctuations drive particles into nonlinear resonances. These particles oscillate around the resonance center located in the A_x-A_y plan satisfying the resonance condition:

$$p\,Q_x(A_x,A_y) + r\,Q_y(A_x,A_y) + m\,Q_s = n$$

where p, r, m and n are integers.

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About LIFETRAC Package

Original Author	Dmitry Shatilov, BINP SB RAS, Novosibirsk, Russia,
General Purpose	weak-strong simulation of beam-beam effects
Method	Macro-particle tracking with a special technique
Particles	Electron-positron, proton-antiproton
Initial Distribution	Gaussian (by default) or from separate text input file
Program Language	FORTRAN 90
Computer Platform	Linux
Compiler	Intel(R) Fortran Compiler for 32-bit applications, Version 7.1
Speed (CAD godzilla)	2.5×10^9 (part x turn) /node/day 10^{11} (part x turn) needs 4-10 days on 10 nodes of gadzilla
Speed (BNL cluster)	5.3×10^9 (part x turn) /node/day 10^{11} (part x turn) needs 19 days on 1 node of cluster.bnl.gov

Advanced Features in LIFETRAC

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- 2-Dimentional coupled optics;
- 3-Dimensional, beam-beam kick computed using interpolated formulae;
- Non-Gaussian transverse density of the strong bunches (superposition of up to 3 Gaussian distributions with different emittances);
- Chromatic modulation of beta functions;
- Longitudinally sliced strong bunch for transformation through main IPs;
- RF cavity;
- Non linear elements for beam-beam compensation;
- Beam tail treatment (by applying more weight on core particles and less weight on tail particles);
- Optics error;
- Noise can be introduced as a short kick at each turn;
- Macro particle of weak beam (~10,000 particles);
- Parallel computation.

LIFETRAC Specifics

1. Originally developed for e^+e^- colliders where the equilibrium is reached within a few dumping times. Then the code is extended to un-equilibrium cases.

2. The beam-beam parameter is an input (not a result). The number of particles and charge/macro-particle are calculated through

$$\xi_{x,y} = \frac{r_p}{2\pi\gamma} \frac{N_p \beta_{x,y}}{\sigma_{x,y}(\sigma_x + \sigma_y)}$$

3. 3D=2D (transverse) + 1D (longitudinal)

4. Statistics are over all macro-particles and all turns within macro-steps. ($N_{mac-part}*N_{turn}<2*10^9$)

Where LIFETRAC has been Successful

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1. Novosibirsk B-factory with flat beam

   Confirmation of reduction on resonance width with increased monochromatization parameter

2. Novosibirsk B-factory with parasitic crossing

3. Novosibirsk ϕ-factory with round beam

4. HERA electron beam

5. Tevotron, FNAL proton and antiproton

   Lifetime and Emittance growth simulation

6. RHIC polarized proton run 2006

   Emittance growth simulation

(The list is limited to my knowledge only)

Simulation Parameters

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Lattice (RHIC Blue ring)	2006 100GeV proton
Blue tunes (x, y)	28.691, 29.690
Yellow tunes (x, y)	28.697, 29.687
Chromaticity (x, y)	2m, 2m
Beta* IP 6, 8, 10, 12, 2, 4	1, 1, 10, 10, 10, 10 [m]
Blue Initial Emittance x, y	15πmmrad (95% norm)
Yellow Initial Emittance x, y	15πmmrad (95% norm)
Initial RMS Beam Length	1m
dE/E	10^{-3}
Aperture x, y, z	8.5σ, 8.5σ, 10.6σ
Beam-beam parameter simulated	0.0~0.018
Initial particle distribution	Gaussian
Number of macro-particles (in core)	10^4
Number of macro-steps simulated	10^2
Number of turns per macro-step	10^5
Total turns simulated	10^7
Total RHIC time simulated	2.13 mins

Tune Scan

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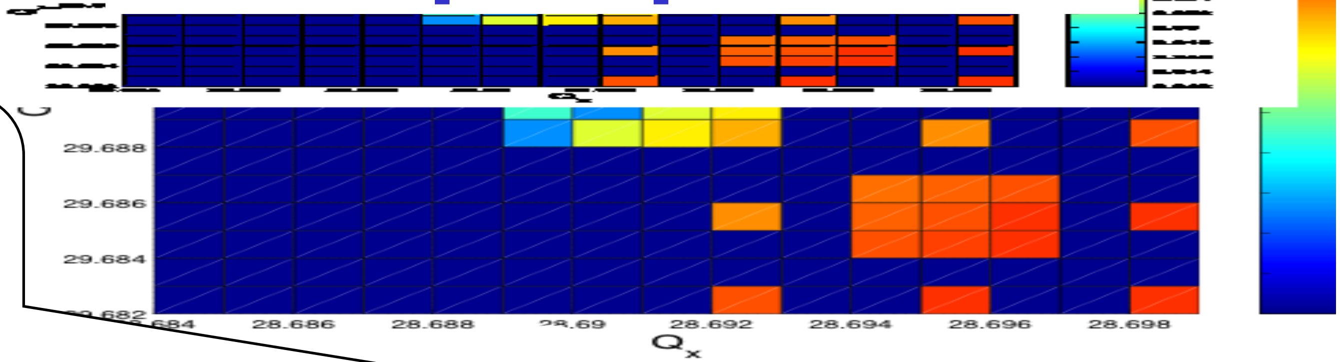
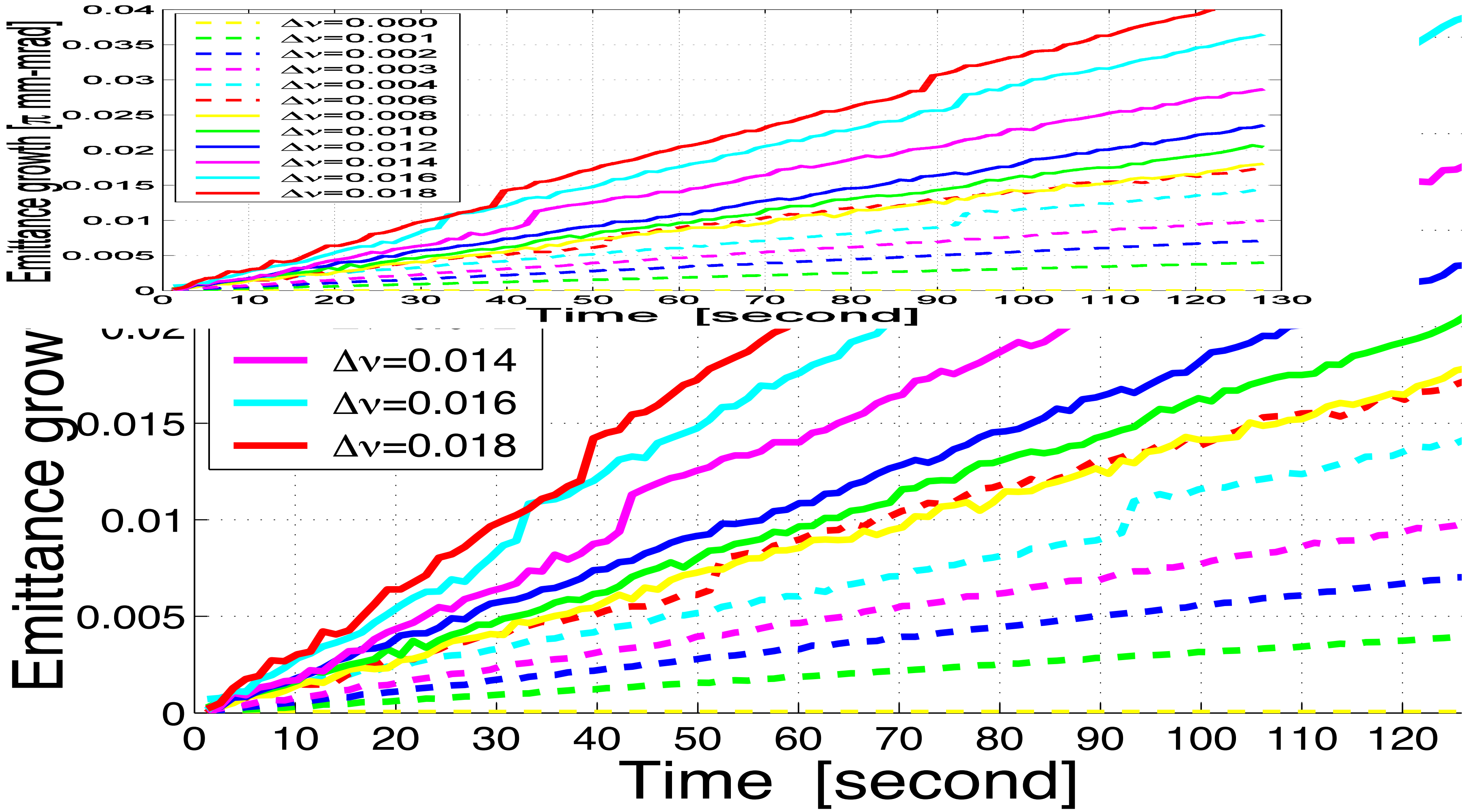
Emittance [cm-rad] after 10^5 turns



This working point is used in all the beam-beam simulations

Emittance Growth from Simulation



Beam Distributions in *(Ax, Ay)* Plane

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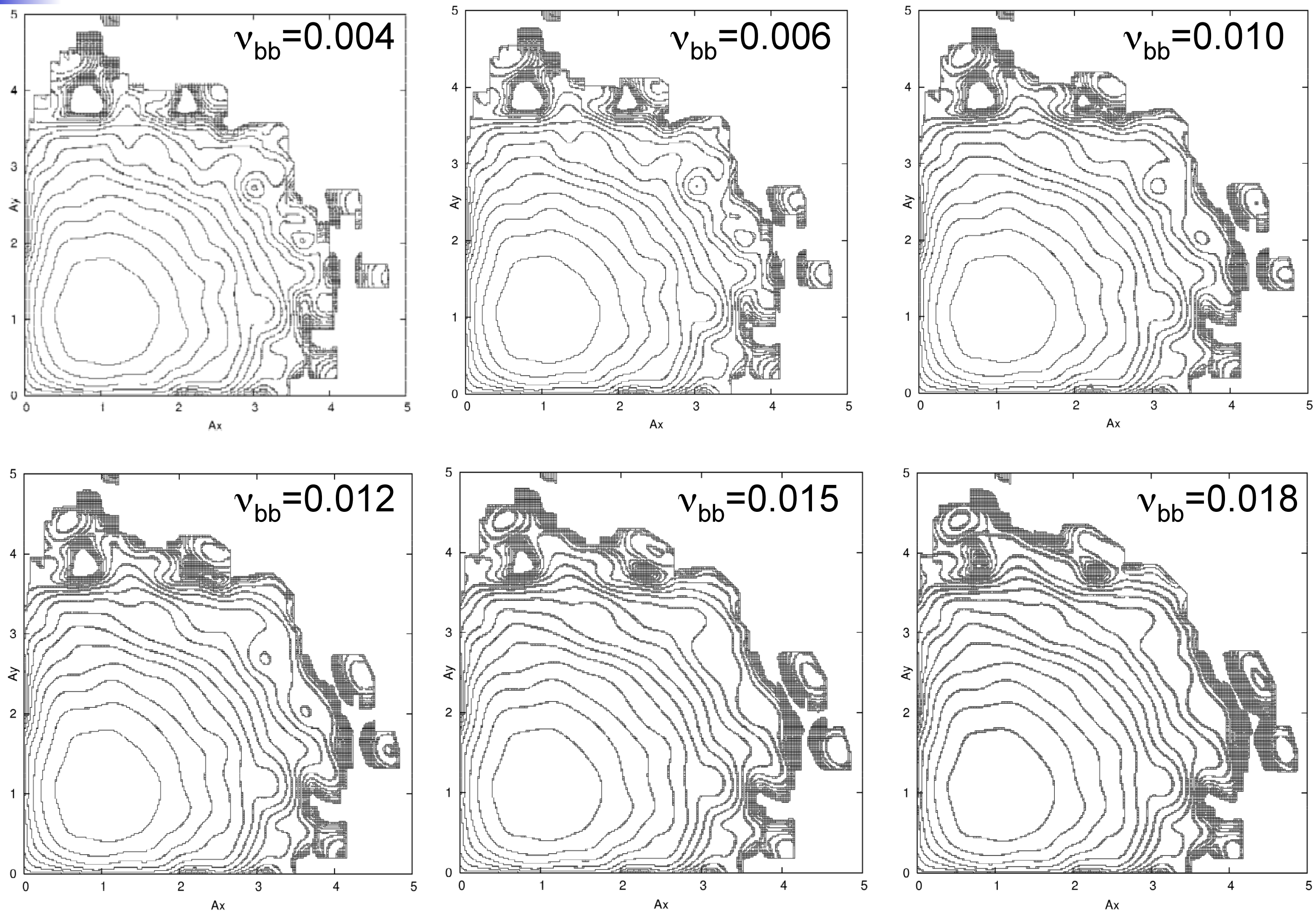

RHIC Emittance Measurement

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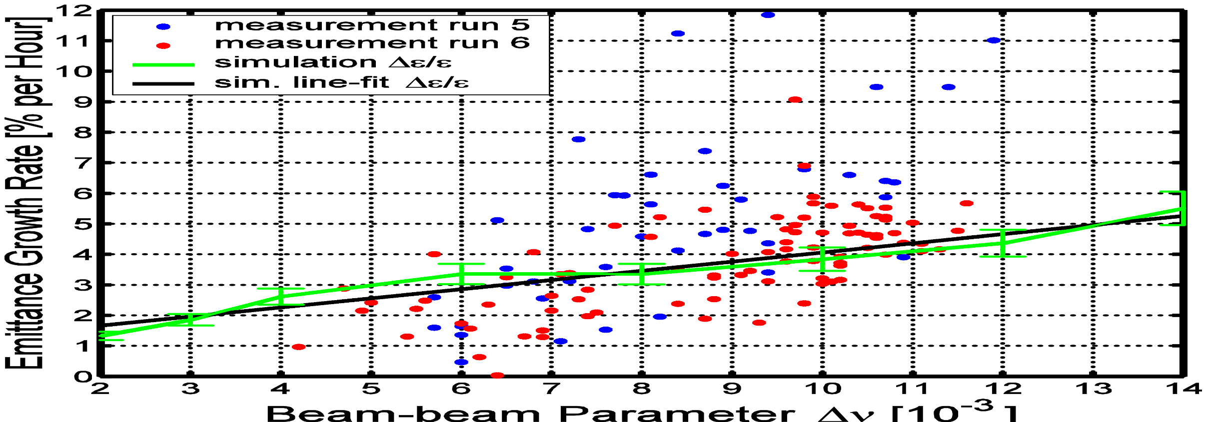
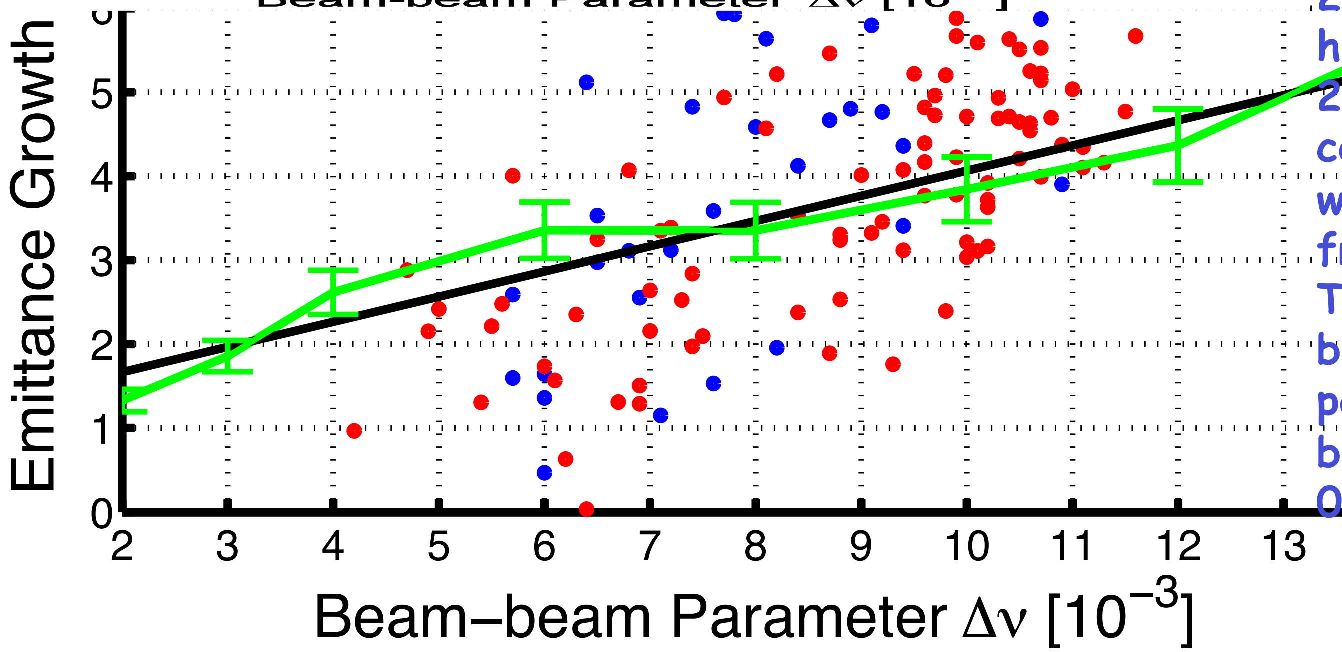
1. All fills in 2005 and 2006 runs are evaluated;
2. Based on the ZDC coincident rates measured during 4 hours of early store (from 1.5 to 5.5 hours after the acceleration ramp event "accramp") at PHENIX and STAR;
3. The 95% normalized beam emittances
4. "Peak Luminosity" = Luminosity at 1.5 hours;
5. "Luminosity lifetime" = average Luminosity lifetime over 4 hours;
6. "Emittance growth rate" = average growth rate over 4 hours.
7. "Beam-beam parameter" = measured at the beginning of the 4 hour period (not averaged).

Emittance Growth Rate





Measurement & observation (S.Y.Zhang)

The bunch intensity in 2006 is much higher than in 2005, but the collision points were reduced from 3 to 2. The largest beam-beam parameters are both limited to 0.012.

Discussion on Comparison of Simulation to Experiment

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The simulation result is slightly higher than the experiment.

Experiment:

The measured emittance was averaged over 4 hours of beam store from 1.5 hours to 5.5 hours after the accelaration ramp event (accramp). The beam-beam parameter was measured at the beginning of the 4 hour period (not averaged). Thus, the average value of beam-beam parameter over the 4 hour period could in fact be lower if the effect of beam intensity drop and the beam emittance growth were included.

Simulation:

Tracks the initial 2.13 minute after the beams are brought to perfect head on collision, when the intensity drop and emittance blow up are both the strongest. This may account for the higher emittance growth rate predicted by the simulation as compared with the calculation based on ZDC measurements.

RHIC RF System Upgrade

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First step:

Use a 9MHz RF system to match the beam injected from AGS into RHIC.

Use the existing 28MHz RF system for store.

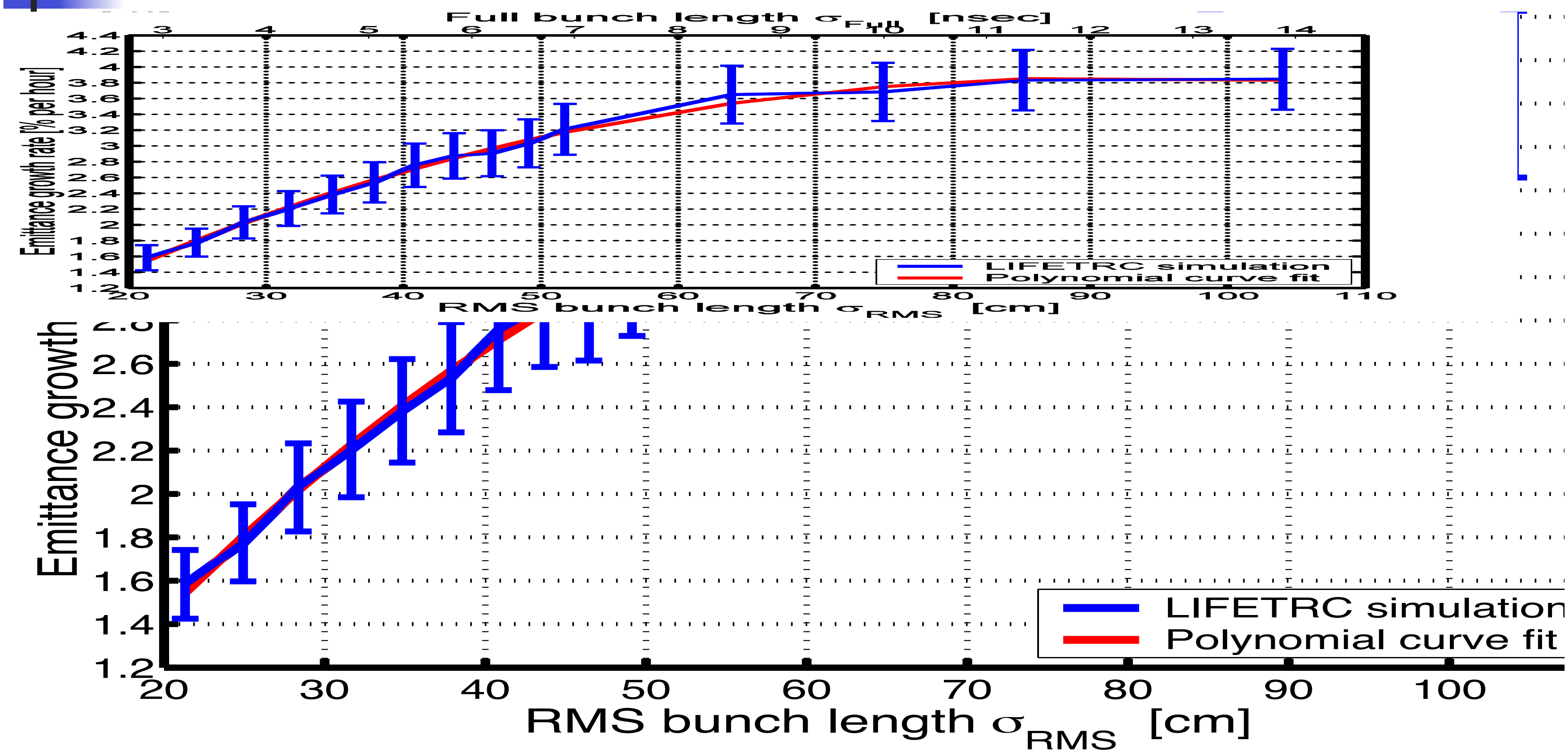
L_{RMS}=58cm, dp/p=0.06% V_{rf}=0.3MV, f_{rf}=28MHz, f_s=44Hz

Second step:

Use a 56MHz superconducting cavity for store.

L_{RMS}=30cm, dp/p=0.11%, V_{rf}=2MV, f_{rf}=56MHz, fs=161Hz

Emittance Growth vs Bunch Length



Emittance growth rate as function of σ_{RMS} from polynomial curve fit:

$$d\varepsilon/\varepsilon = 0.01324\,\sigma_{RMS}^3 - 0.0727\,\sigma_{RMS}^2 + 0.101\sigma_{RMS} - 0.003$$

Conclusion and future work

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1. The simulations of RHIC 2006 run and the measurement from ZDC are in reasonably good agreement.

2. Magnet nonlinearities and noises are not included so far.
   A) Can't directly tack MAD nonlinear model as input.
   B) There is a plan to build a more advanced model or, at least, include the magnet errors in the form of global noise matrix.

3. The cooling effect could be investigated in the form of damping. (Currently looking into related issues)

2. Simulations on emittance growth vs. bunch length gave incoraging result. However, we need more detailed studies with the conditions of proposed RF upgrades.

   Currently in the prograss of setting up models for simulations with
   A) 28MHz RF system
   B) 56MHz RF system
   C) RF system for 250GeV protons